Constellation-X Mirror Fabrication Development: Achievements, Problems, and Prospects

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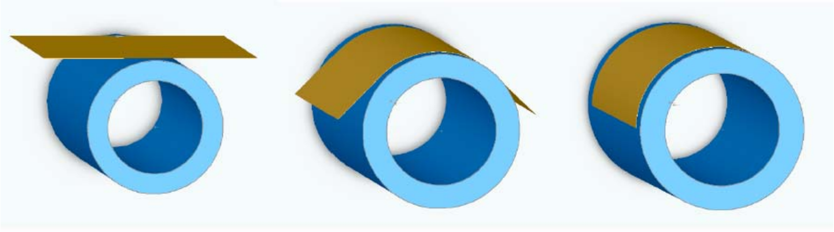
Fabrication Process



- Start with a sheet of commercially available borosilicate glass, 0.4mm thick
- Place it on a fused quartz mandrel whose surface has been treated to prevent sticking and provide other necessary properties for slumping
- Start a temperature cycle between between 20 and 600 degrees C

Use an epoxy replication procedure to further improve the substrate if necessary

SXT Mandrel Challenge in Perspective

	Con-X	XMM	Chandra	JWST
No. of Assy.	4	3	1	1
No. of Shells per Assy.	216	58	4	NA
Total Mirror Area (m^2) of the Observatory	**883**	158	19	36
Total Mandrel Area (m^2)	**28**	53	19	36

Manufacture of SXT mandrels is NOT challenging in historic terms.

- **Comparable to, or easier than, XMM's mandrels because of smaller area**
- **Much easier than Chandra's mirrors because of much less stringent figure requirements**
- **Much easier than JWST mirrors because there are no lightweighting or cryogenic requirements**

Development Strategy

- Start with a technique that meets three (effective area, mass, and production cost) of the four requirements, work on the fourth one (angular resolution)
- Pursue **reproducibility**, or process determinism: making all the mirrors look alike
- Pursue **traceability**: making all the mirrors look like the mandrels
- Combine reproducibility and traceability to finally achieve **capability**

Mirror Segment Description

Interferometer

Coordinate Measuring Machine

$$\rho(z,\phi) = \rho_0(\phi) + z \cdot \tan\theta(\phi) - \left(\frac{2z}{L}\right)^2 \cdot s(\phi) + R(z,\phi)$$

$$\rho_0(\phi) = \rho_0 + \Delta\rho(\phi)$$

$$\theta(\phi) = \theta_0 + \Delta\theta(\phi)$$

$$s(\phi) = s_0 + \Delta s(\phi)$$

By definition/convention, all the Delta terms (azimuth dependent) have zero means. So does also the R(z,phi) term.

Mirror Segment Error Allocation

Nomenclature		Comment
Radius	Average Radius	Azimuth and Z independent
	Radius Variation	Azimuth dependent, Having frequency content
Cone Angle	Average Cone Angle	Azimuth and Z independent
	Cone Angle Variation	Azimuth dependent; Having frequency content
Sag	Average Sag	Azimuth and Z independent
	Sag Variation	Azimuth dependent; Having frequency content
Residual	Axial Figure	Azimuth and Z dependent; Having frequency content
	Azimuthal Figure	Azimuth and Z dependent; Having frequency dependent

Quantity	Slope Error (“)	Two-Reflection Equivalent HPD (“)
Low Frequency (200-20mm)	1.6	6.1
Mid-Frequency (20-1mm)	1.6	6.1
Microrough-ness (1mm-1micron)	NA	NA

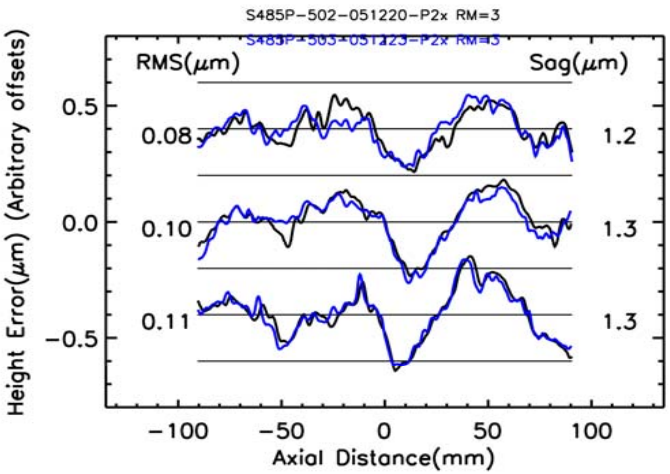
What Have We Been Doing?

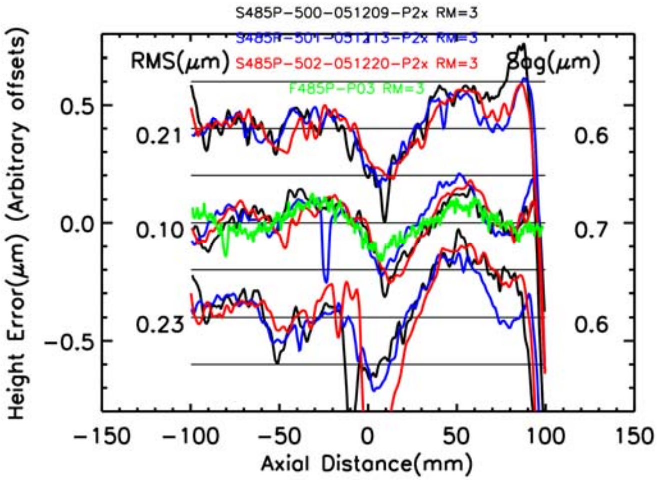
- Creating/inventing a mandrel surface treatment process that must meet a number of conflicting requirements
- Devising temperature cycles that take into account both thermal and mechanical properties of the slumping process
- Figuring out, at any given time, what's the dominant factor that affects mirror quality
  - Temperature cycle
  - Mandrel surface treatment
  - Slumping environment cleanliness
  - Mandrel surface treatment
  - Slumping environment cleanliness
  - …..

What Significant Things Have We Learned?

- Three different methods of treating forming mandrel surfaces
- One thermal run-away process that has to be controlled adequately before a good mirror substrate can be formed
- One method to rein in the thermal instability

Repeatability of Slumping

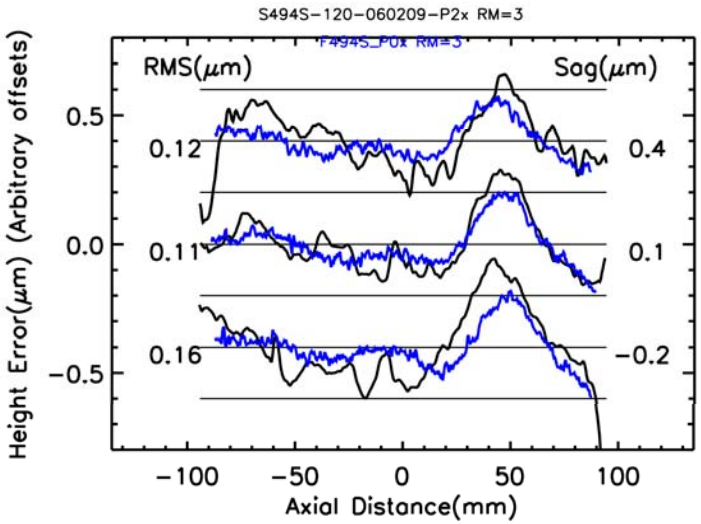


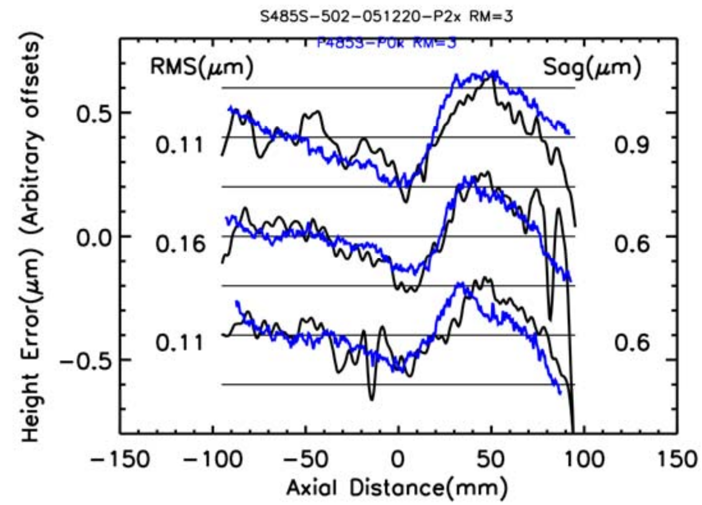


- Typical repeatability: 50nm RMS
- Best repeatability: 20nm RMS
- These numbers are upper limits; they are dominated by metrology repeatability and cross-registration uncertainties. In all likelihood, the real repeatability is much better.

Traceability to Mandrels

Black=Substrate; Blue=Mandrel





- Given uncertainty in the metrology process, the agreement between mandrel and substrate/mirror is excellent
- This implies that better mandrels will lead to better substrates/mirrors

How Good Are the Current Mirrors?

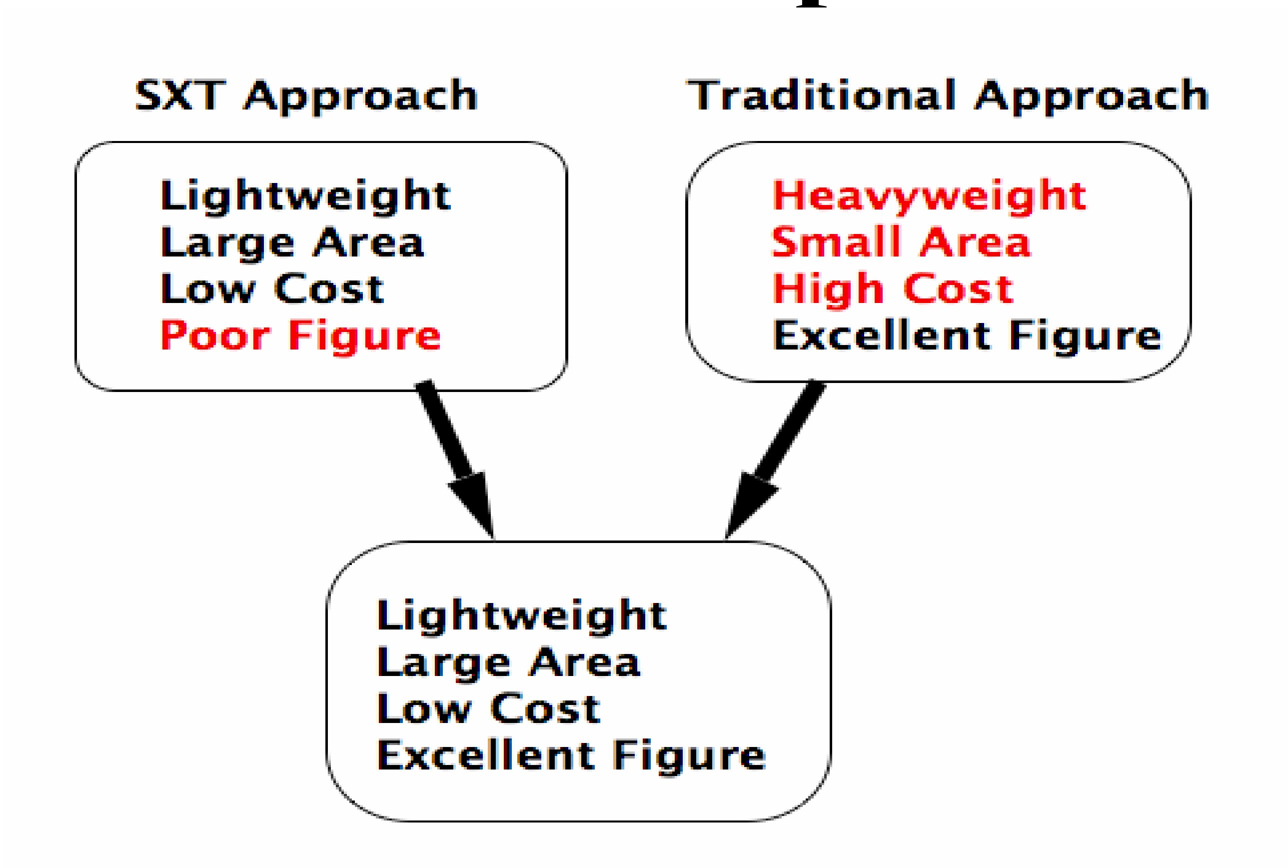
	HPD (arcsec; 2 Reflection Equivalent) (before epoxy replication)			HPD (arcsec; 2 Reflection Equivalent) (expected after epoxy replication)		
Mirror ID (Consecutive Slumping Cycles)	Low-Frequency Figure (arcsec)	Mid-frequency (arcsec)	Overall (arcsec)	Low-Frequency Figure (arcsec)	Mid-frequency (arcsec)	Overall (arcsec)
S485P-500	7.7	18.3	19.9	7.7	6.1	9.8
S485P-501	7.8	12.9	15.1	7.8	4.3	8.9
S485P-502	7.8	11.9	14.2	7.8	4.0	8.8
S485P-503	7.4	13.8	15.7	7.4	4.6	8.7
S485P-600	8.2	15.1	17.2	8.2	5.0	9.6
S485P-601	7.9	11.4	13.9	7.9	4.0	8.9
S485P-602	7.0	14.6	16.2	7.0	4.9	8.5
S485P-603	6.6	13.0	14.6	6.6	4.3	7.9
S494P-120	5.7	12.6	13.8	5.7	4.2	7.1
S494S-120	7.0	10.6	12.7	7.0	4.0	8.1
S494P-121	6.0	11.2	12.7	6.0	4.0	7.2
Average	7.2	13.2	15.1	7.2	4.5	8.5

Requirement: 9.0

Summary of Status

- We have achieved excellent repeatability in slumping substrates
  - Typical: 50nm RMS
  - Best: 20nm RMS
  - Without epoxy replication, these substrates, when properly integrated, are expected to perform at 20 arcsec level (HPD, 2 reflections)
  - With epoxy replication, the resulting replicas, when properly integrated, are expected to perform at 10 to 15 arcsec level (HPD, 2 reflections), meeting or exceeding Con-X baseline requirement
- The characteristics of these substrates are
  - Resembling the mandrel in low frequency (20 to 200mm) figure
  - Having additional mid-frequency (spatial periods: 2 to 20mm) errors resulting from the slumping process
  - Once finished with epoxy replication, the resulting replicas are expected to meet or exceed SXT baseline requirements

Application to Normal Incidence Optics



Problems and Solutions

- The low frequency figure of the substrate is somewhat worse (~50%) than that of the forming mandrel
  - Cause: the release layer is not uniform, thereby degrading the mandrel figure
  - Solution: better application and improved post-application treatment
  - Probability of Success: >90%
- The substrate has significant amounts of mid-frequency figure error
  - Cause: dust from the slumping environment and detritus resulting from the release layer
  - Solution:
    - Better slumping environment: clean oven
    - Improved mandrel surface release layer
  - Probability of Success: unlikely for acquiring a clean soon; ~70% for improved release layer
- The epoxy replication process slightly degrades the low frequency figure and does not always copy the mid or high frequency figure of the replication mandrel
  - Cause: particulates and other contamination on the replication mandrel surface
  - Solution: a new replication mandrel coated in-situ
  - Probability of Success: unlikely in short term due to budget constraints

Prospects

- Almost all technological aspects of the mirror development are understood and going very well:
  - Problems are well defined
  - Solutions are available
- In all likelihood, we will be able to do significantly better than the SXT baseline requirements. By the end of this year we should be able to quantitatively gauge whether the present technology can achieve the SXT goal of 5 arcsec.

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